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The Equipment and Functions of an Illumination Laboratory

By H. F. STEPHENSON, B.Sc.(Eng.), A.M.I.E.E., *(Member)*.

Summary

This paper reviews typical problems arising in an Illumination Laboratory and the apparatus and techniques used in their solution. A distinction is drawn between the functions of Photometric and Illumination Laboratories. The appraisal of lighting equipment, lighting systems and the many testing procedures which are remote from formal photometry are discussed. The requirements of a building suitable for this type of work are also described.

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(1) Introduction

A photometric laboratory is concerned mainly with the measurement of light; an illumination laboratory is concerned with its utilisation. Photometry is used in an illumination laboratory only as a means to an end and the techniques must be versatile rather than precise.

This paper reviews typical problems and the equipment used in their solution,

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illustrated mostly from the laboratory with which the author is associated. Some of these problems arise also in the photometric standardising laboratory and have been described elsewhere, but others are remote from formal photometry and little published information is available.

(2) Problems Arising in an Illumination Laboratory

A review of problems can at best indicate only broad divisions. Not all illumination laboratories need to cover the full range mentioned and requirements vary from the routine testing of a limited range of products to those of a larger group responsible for photometric standardisation, appraisal of many different types of equipment and research into particular applications. In some laboratories work may be sectionalised in various ways and equipment will vary accordingly.

The principal problems occurring in the illumination laboratory are summarised in Table 1. This indicates the essential apparatus needed and refers the reader to the section of the paper dealing with it.

(3) Problems of Photometric Measurement

3.1) The Significance of Photometric Measurements

The design of a measuring technique must be preceded by a clear understanding of the quantity to be measured and its significance when it has been measured. The link between photometric measurements and visual effect is of first importance, for the photometrist measures physical quantities, but expresses them on a scale chosen to conform approximately with the visual effect under specified conditions. In other conditions the use of the photometric scale can produce anomalous results, for example when the luminance is low or viewing conditions are other than those specified.

The performance of lighting equipment is frequently expressed in terms of luminous intensity, but this procedure is valid only if the measurements are made in conditions in which the inverse square law applies sufficiently accurately for the purpose in hand. The minimum distance necessary may be large and measurements made inside this distance cannot properly be expressed in terms of luminous intensity. Similarly, calculations using the inverse square law are invalid if the distances involved in the calculations are inside this minimum distance. These considerations often apply to large equipment, including most fluorescent interior lighting fittings, and to narrow beam projectors; the complexity of the apparatus needed for a particular measurement, or the approximations permissible in calculations, depend on the accuracy required.

The basic photometric concepts have been fully discussed in the literature[1,2].

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3.2) Accuracy of Measurement in Photometric and Illumination Laboratories

A photometric laboratory is chiefly concerned with measurements of the fundamental characteristics of lamps and materials. Such measurements may be required to establish reference standards for use in other branches of its work or for a separate illumination laboratory, in the control of manufacture, or in life tests. For such measurements the photometric accuracy and the measuring precision need to be high, usually of the order of 1-2 per cent. in absolute value or better.

In the illumination laboratory, photometry is used either to assess the performance of a lighting fitting or to investigate a lighting task. Whilst calibration of the photometric tools or particular visual studies may also call for an accuracy of 1-2 per cent., the more general problems of lighting and appraisal of fittings rarely justify elaborate and precise measurement. Fairly wide tolerances are allowable, not only because the eye is insensitive to small changes in luminance, but because of the effect of manufacturing tolerances on the reproducibility of lighting equipment.

Though it could well be argued from this that few measurements need to have

Table 1.

Analysis of Principal Problems in an Illumination Laboratory

	PROBLEM	PRINCIPAL EQUIPMENT	SECTION
1	Basic Photometry (Directional intensity of lamps, standardisation of filters, sector discs, colour temperatures,	Reference lamps, photometer bench and auxiliary equipment or "Universal" photometer.	4
2	Calibration of portable illumination and luminance photometers.	Reference lamps, photometer bench, and standard diffusing surface.	4
3	Measurement of luminous flux.	Integrator or intensity distribution photometer.	4.3 6
4	Distribution of luminous intensity.		
	(*a*) Small fittings with vertical axis of symmetry.	Intensity distribution photometer.	6.1
	(*b*) Large fittings, some with horizontal axis of symmetry; small projectors.	Turntable distribution photometer.	6.2
	(*c*) Large narrow-beam projectors.	Long photometric range; turntable, receptor, standard projector and auxiliary gear.	6.3
5	Study of spotlights and image projectors.	Projection screen and portable photometers.	6.2
6	Illumination surveys.		
	(*a*) Single fitting.	Overhead fitting rotator and photocell equipment.	6.5 5.2
	(*b*) Several fittings or installations.	Portable photometers or photocell and galvanometer trolley.	5.1
7	Luminance surveys.	Luminance photometers, telephotometers. Specialised photographic equipment.	5.1 7
8	Outdoor field trials.	Portable photometers, telephones, simple surveying equipment, transport.	11
9	Photography.		
	(*a*) Record photography.	Stand and miniature cameras, enlarger and darkroom.	7
	(*b*) Specialist photography (Photographic photometry, Standard Representation photography.)	Specialised equipment, densitometer.	7
10	Photometric properties of materials.		
	(*a*) Reflection and transmission.	Reflectometers, goniophotometer, "Ray path" equipment.	9
	(*b*) Colour.	Colorimeter, comparators, limit glasses, photometer bench.	5.3
11	Thermal experiments.	Screened enclosures, thermocouple and resistance thermometer equipment; temperature indicating paints, smoke producers; Schlieren equipment, immersion tank.	8 9
12	Life and weather proofing testing.	Life test and exposure test stations; rain splash, spray, tank for submersible equipment.	10
13	Mechanical testing.	Impact and static load equipment; shaking and vibration machines.	9
14	Study of lighting problems.	Models; laboratory simulations built *ad hoc*.	12

an accuracy of better than, say, 15-20 per cent., higher accuracies are desirable from other points of view. Many tests take place over a long time so that the photometric level must be known and maintained if the results are to be significant. It may, furthermore, be necessary to check or certify compliance with a specification which involves a higher accuracy. Such considerations necessitate the use of most of the accepted photometric procedures and precautions of the standards laboratory to avoid systematic errors. Measuring techniques can be varied to suit particular requirements but should always retain sufficient accuracy to keep the experiment under control; an absolute accuracy of about 5 per cent. is usually sufficient.

(4) Fundamental Equipment Common to Standards and Illumination Laboratories

(4.1) Reference Lamps

Two classes of reference lamps are required, calibrated respectively for directional intensity and for total light output. Some of the directional reference lamps may also be calibrated for colour temperature at a number of voltages. Directional reference lamps, which should be mounted in N.P.L.-type holders[3], provide the basis for the measurement of luminous intensity, and for calibrating illuminometers and luminance meters. Total output reference lamps are used both for calibrating photometric integrators and when photometering lighting fittings so that the results may be given in terms of a lamp of stated performance.

In the preparation of a set of reference lamps each is aged, selected for photometric and electrical stability, and has as nearly as possible the nominal light centre length and other dimensions. Sufficient lamps should be available in each rating to allow for interchecking and to enable the periodic recalibration schedule to be carried through without interruption of work. Many precautions need to be observed in using these lamps if their outputs are to be reproducible to the required accuracy, special care being necessary with discharge lamps[4, 5].

(4.2) Photometer Bench and Equipment

The photometer bench and reference lamps provide the basic equipment for photometric work[6]. One important use in the illumination laboratory is for calibrating portable visual and photoelectric photometers. Fig. 1 illustrates arrangements for photoelectric equipment, in which the photometer is held on an adjustable

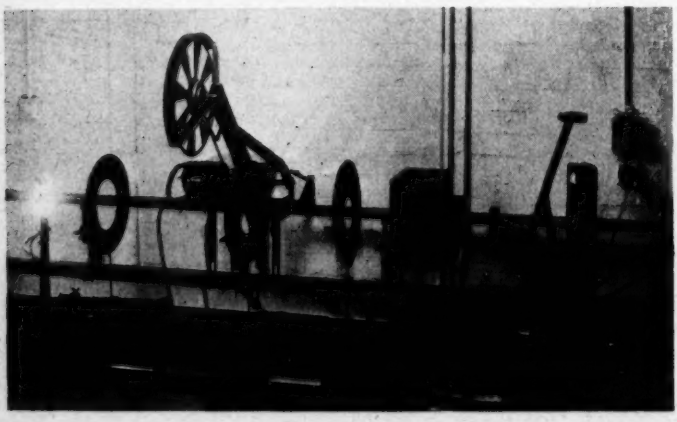


Fig. 1. Arrangement of photometer bench for calibrating photoelectric photometer.

mounting fixed to an arm hinged at the wall. Screening is checked by swinging the arm clear and making a visual inspection from the position normally occupied by the photocell.

The equipment of the bench should include a Lummer-Brodhun photometer head with eyepieces giving a 2 deg. field, and a 6 deg. or larger field size for colour matching. Particular classes of work will demand additional accessories, for example, sector discs and change-over filter holders in transmission measurements.

Where laboratory space is limited the "Universal" emission-type photometer(7), fitted with a Preston liquid filter(8), forms an alternative to the photometer bench for some types of measurement, since it provides a photometric scale in itself. This instrument also makes possible precision photometry without the need for skilled observers.

(4.3) Photometric Integrator

If many measurements of the total light output of lamps or routine tests on many similar fittings are required, a large photometric integrator(9) will be needed. The use of photometric integrators in the illumination laboratory is discussed in Section (6.4), but the light flux is often more conveniently calculated from the light distribution determined on an intensity distribution photometer.

(4.4) Electrical Supplies and Instruments for Photometry

Well organised electrical supplies are essential; they must be stable in voltage and frequency, preferably to about 0.25 per cent. For photometry with tungsten lamps a D.C. battery supply, though desirable, is not essential; for most purposes a stabilised A.C. supply, with a tapped transformer giving a large range of voltages and a good wave form, is suitable. Resistances or variable transformers are required for control purposes.

Electrical instruments of the sub-standard class(10) are needed, the types and ratings depending on the work undertaken. For A.C. circuits, dynamometer-type instruments are preferable: for discharge lamps, instruments must be unaffected by distorted wave forms(11), and for low wattage fluorescent lamps instruments should have very low power consumption(12). Galvanometers are discussed under Section (5.2.5).

In addition an accurate set of instruments, preferably of the laboratory standard class, is desirable. These instruments are not intended for routine work but are kept for bench photometry and as reference standards for checking other instruments.

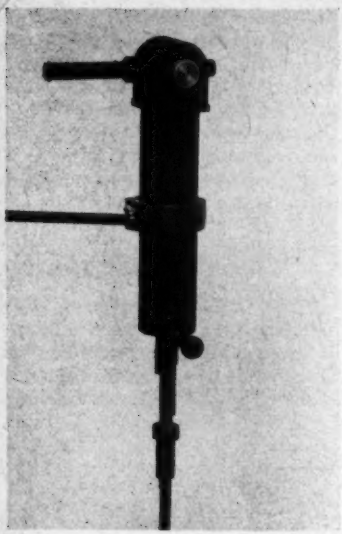
(5) Fundamental Photometric Equipment Peculiar to the Illumination Laboratory

(5.1) Illumination and Luminance Photometers

The visual illuminometer in its various forms is one of the most valuable instruments in the illumination laboratory. It can be used for both illumination and luminance measurements and can be adapted for telephotometry. It is often used with such instruments as reflectometers and is useful as a transfer instrument for calibrating photoelectric equipment. The characteristics of these photometers are specified in B.S. 230.

Where precise measurements are needed the instruments commercially available may require modification, for the overall accuracy is rarely better than 5 per cent. even with skilled observers. Improvements required include precise control of the illuminometer lamp, a contrast type of photometer prism and careful attention to screening within the photometer to improve the scale linearity(13).

Two instruments, each utilising the inverse square principle, are shown in Figs. 2a and 2b, and the optical systems in Figs. 3a and 3b. The instrument of Figs. 2a and 3a is a straightforward inverse-square illuminometer based upon the Macbeth photo-



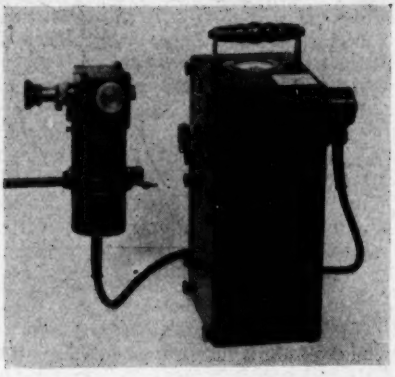


Fig. 2 (a). *(Left)*. Illuminometer based on Macbeth photometer.

(b). *(Above)*. Illuminometer and control box designed by J. M. Waldram.

meter with photometric screening along the photometer tube. The other instrument, designed by J. M. Waldram, is also an inverse-square instrument on the Martens principle using a moving 90 deg. reflecting prism. Both instruments have Lummer-Brodhun contrast prisms and the range-changing filters are mounted on a drum. The telecentric stop principle is used in the eyepieces so that the external field of view is small. The instruments may be adapted for use as telephotometers by changing the prism and adding a telescope, or as microphotometers by adding front lenses.

The circuit for controlling the illuminometer lamp in one instrument is a Wheatstone bridge network in which the lamp forms one of the arms[14]. The other instrument employs a voltmeter connected directly to the lamp and is controlled by a specially designed rheostat.

Other forms of telephotometer and luminance meter are the Street Luminance meter[15], useful for approximate work at low levels, the S.E.I. (Dunn and Plant) exposure photometer[16], which is easily portable and covers a wide range with moderate accuracy, and the Schuil telephotometer[17], a more precise instrument covering a very wide luminance range. The Macbeth illuminometer and the Lumeter can be adapted to many forms of luminance measurement. Collier[18] describes several specialised instruments, and Robinson[19] reviews more recent instruments used in "Brightness Engineering."

Measurement at very low luminances presents special problems, and most of the instruments already mentioned are unsuitable. The conditions necessary for a suitable instrument and the problems involved in the departure from the high-luminance[1] small-field conditions in which the photometric scale is established, have been discussed[20, 21, 22].

Portable photoelectric illumination meters are convenient for many measurements both in the laboratory and in field tests. Instruments should be available capable of measuring a wide range of illuminations, from fractions of a lm./ft.^{2} for street lighting work to many hundred lm./ft.^{2}. Various patterns are produced commercially and are usually designed to comply with B.S. 667.

Luminance measurements in installations are not easy to make with photo-

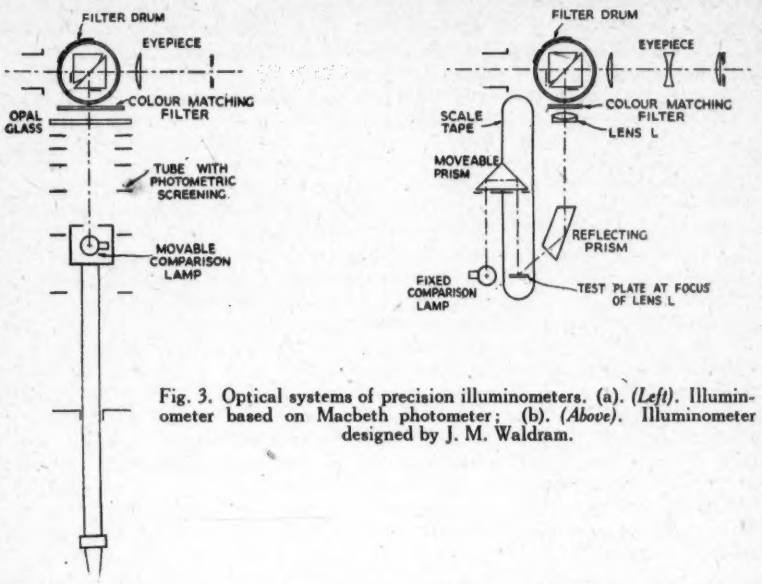


Fig. 3. Optical systems of precision illuminometers. (a). *(Left)*. Illuminometer based on Macbeth photometer; (b). *(Above)*. Illuminometer designed by J. M. Waldram.

electric instruments, and except for specialised applications[23] visual instruments are usually more convenient.

(5.2) Photoelectric Photometry in the Illumination Laboratory

(5.2.1) *Use of Photocells in the Illumination Laboratory.*

The preparation of light distribution data for lighting equipment involves taking many readings, and photoelectric methods are quicker and less fatiguing than visual. Photovoltaic cells are commonly used, and sufficient repetition precision and approach to linearity can be obtained provided adequate precautions are taken. For some purposes the photoemissive cell is essential because of its higher sensitivity and close approach to linearity, and also because its spectral sensitivity can be matched closely to that of the C.I.E. "average eye." The photoemissive cell, however, is best suited to bench or sphere photometry where a higher order of accuracy and relatively few observations are required.

The properties of the two types of photocell have been described at length[24, 7], and only a few of the special problems in the use of photovoltaic cells in the illumination laboratory will be discussed. The chief application for these photocells is in apparatus for obtaining light distribution curves where a deflection method of measurement is generally more convenient.

(5.2.2.) *Choice of Photocell.*

Considerable improvements have been made recently in the properties of selenium photovoltaic cells, but some lack of uniformity in performance occurs even in cells manufactured in the same batch[25, 26]. Photocells required for photometric work therefore need to be specially selected. Since the external circuit affects the performance of the photocell, selection should preferably be made on the type of circuit with which the cell is to be used.

The stability of the photocell directly affects the measuring precision obtainable, fatigue and temperature co-efficient combining to introduce uncertainties in the

current produced for a given illumination. In practice the temperature co-efficient of modern cells is small when the cell is used with a suitable external resistance, and since temperature variations in the laboratory are not excessive little trouble should be experienced, although it may be troublesome in outdoor night tests. Other factors affecting the choice of cell include the sensitivity required and the area of cell to be used(24).

(5.2.3.) *Cosine Response of Photocells.*

The departure of the response of a photocell from the cosine law for light incident obliquely is well known(24). Photovoltaic cells coated with a matt lacquer show only small discrepancies at angles up to 65 deg.(7), but above this angle the errors increase rapidly. With polar co-ordinate distribution photometers the light strikes the photocell normally, or at a constant angle, and the error is avoided, but difficulties arise in measuring illumination distributions.

In the photometry of interior installations the fraction of the incident light which reaches the photocell very obliquely is usually small, and with a photocell having a good cosine response the correction involved is insignificant. In street lighting, however, it may be significant; sometimes the error can be avoided by suitable experimental procedures. Techniques such as pointing the photocell towards the light sources(7, 24) are sometimes satisfactory and an extension of this principle for the photometry of fluorescent fittings has been described(27).

Many devices for improving the cosine response have been suggested(28) although few are practicable. One method described by Pleijel(29) has been used successfully in daylight investigations.

(5.2.4.) *Spectral Sensitivity of Photocells.*

The use of photocells in the comparison of light sources having different spectral energy distributions and correction of the spectral response to that of the C.I.E. "average eye" by filters has been discussed recently(30).

Filters used over the photocell for this purpose are not satisfactory except when the light reaches the photocell normally or at one fixed angle, as in distribution photometers. Not only is the cosine error increased due to reflection at the filter surface but, since the length of the light path in the filter varies with the angle of incidence, the "average eye" correction is impaired. Where good cosine response is essential filters are not used and a visual calibration of the photocell or correcting factors are employed to allow for the different light sources. Since the spectral response of the photocell extends into the ultra-violet and the infra-red, errors may occur in some types of measurement. If these errors cannot be avoided by calibration techniques, additional filters may be necessary. Gelatine filters, sometimes used for approximate spectral sensitivity correction, usually transmit both infra-red and ultra-violet radiation; glass filters also may transmit some infra-red radiation.

(5.2.5) *Photocell/Galvanometer Combinations.*

In the laboratory, reflecting galvanometers are used for the deflection method of measuring the current output from a photovoltaic cell. They are convenient and adaptable, and are normally used critically damped in a variable sensitivity circuit.

Modern taut suspension galvanometers are much more sensitive than earlier designs. This improvement however has sometimes been obtained at the expense of linearity, and with the higher magnetic flux densities now used the galvanometer is more susceptible to the effect of magnetic dust collected during use. It is therefore important to check the galvanometer for electrical linearity both initially and periodically in service. The use of short period galvanometers is convenient, their sensitivity being sufficient for photometry when used with photovoltaic cells of about 45 mm. diameter. Shortening the periodic time has several advantages; the thicker suspension strips give greater controlling torque and improve the zero keeping qualities

and linearity. Galvanometers, unlike most electrical indicating instruments, are not fitted with a series swamping resistance and have a temperature co-efficient of about 0.4 per cent. per deg. C.

Circuits used with galvanometers for sensitivity variation affect the load resistance, which should not exceed about 200 ohms for illumination values up to 50 lm./ft.^{2}. The principle of most circuits is that of the Ayrton-Mather universal shunt[31] adapted to give critical damping. In the simple circuit (Fig. 4a) the shunting resistance R provides critical damping of the galvanometer. Sensitivity is altered by moving the tapping point, and at any position the load resistance across the photocell is the combined resistance of the tapped section of the shunt and the remainder of the shunt plus the galvanometer coil resistance. The highest value occurs at mid-position, and it is this value which determines whether the arrangement will be satisfactory for photometric use. For example, a 50-ohm galvanometer with a damping resistance of 1,000 ohms gives a resistance burden at mid-point of about 250 ohms, which is in the region of the upper limit allowable.

This simple circuit, however, gives insufficiently fine control, and a preferred circuit is that shown in Fig. 4b. This provides coarse and fine control of uniform

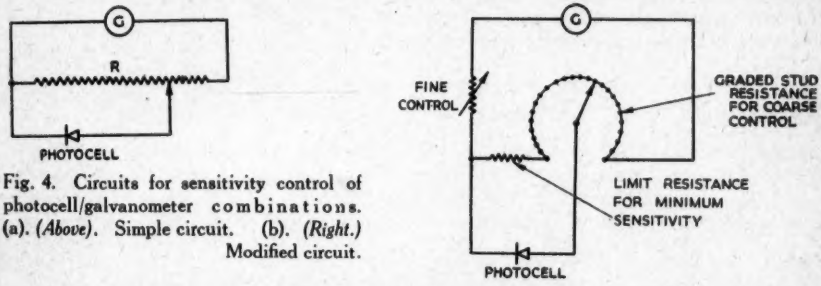


Fig. 4. Circuits for sensitivity control of photocell/galvanometer combinations. (a). *(Above)*. Simple circuit. (b). *(Right.)* Modified circuit.

sensitivity over a wide range; it can also be arranged that if the illumination on the photocell exceeds the value at which the departure from linearity becomes serious, the galvanometer goes off scale.

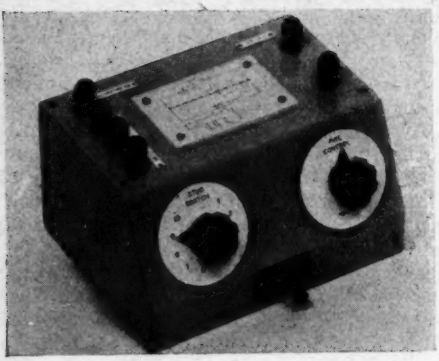
The characteristics of some useful photocell/galvanometer combinations are given in Table 2.

Table 2.

Characteristics of Some Photovoltaic Cell/Galvanometer Combinations

Cell Dia. (mm.)	Galvanometer Coil Resistance (ohms)	Approx. Critical Damping Resistance (ohms)	Periodic Time. (secs.)	Sensitivity. Deflection per Incident lm./ft.^{2} at 1 metre Scale Distance. (cm.)
45	50	1200	2	65
45	50	1000	1.5	37
45	50	500	1	17
45	10	90	1	8
45	140	1000	0.5	26
12	140	1000	0.5	2

A versatile equipment for laboratory use is a photovoltaic cell connected by a long lead to a trolley in which a short period reflecting galvanometer with lamp and scale is permanently mounted. A sensitivity control using the circuit of Fig 4(b) is



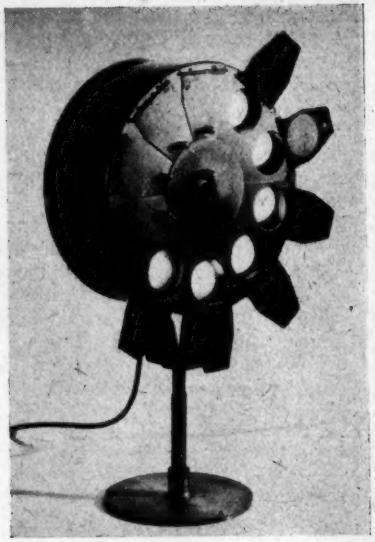


Fig. 5. Linearity testers. (a). *(Above)*. Galvanometer linearity tester; (b). Photometric linearity tester.

incorporated and the apparaus can be used for illumination measurements, distribution photometry and for many other purposes. This arrangement, which can be seen in Fig. 11(b), is especially useful in a small laboratory where the work does not justify maintaining separate photocell/galvanometer combinations on each piece of apparatus.

(5.2.6) *Scale Linearity Checking Devices.*

It is necessary to check frequently the linearity of the scales of photometric instruments. Such measurements are best made by the summation method[32]. A convenient portable apparatus (Fig. 5a) incorporates 10 lamps, any number of which can be exposed as desired. The model shown is mounted on a N.P.L.-type lamp-holder stalk and can be used either in a carriage on the photometer bench or in the laboratory on the distribution photometers.

A second linearity tester for checking the relation between the deflection of the

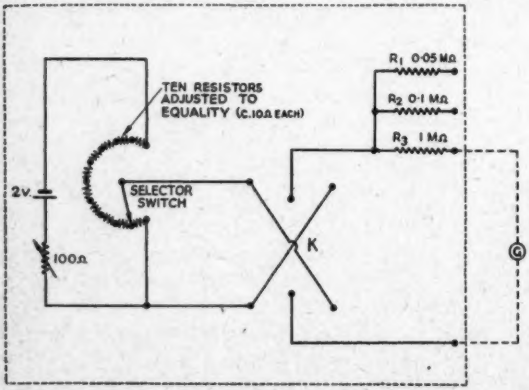


Fig. 6. Circuit of galvanometer linearity tester.

galvanometer and the current in the coil is of value both in selecting galvanometers for use in photocell/galvanometer combinations and for checking apparatus already in service. The tester is shown in Fig. 5b and the circuit in Fig. 6. In this circuit a current is passed through a tapped resistance consisting of 10 resistance coils, all accurately adjusted to equality. This forms a potential divider; the current through the galvanometer will be proportional to the number of coils selected.

In the instrument shown three high resistors, R_1, R_2 and R_3 are included, giving alternative ranges; the coil resistances of galvanometers suitable for use with photocells are negligibly small by comparison. A reversing and on-off switch K enables the galvanometer to be checked to either side of zero, and the fine control resistance in the main circuit allows the deflection to be set to a convenient value.

Both the linearity test sets described are portable and enable permanent photocell/galvanometer combinations to be checked on site as part of a regular maintenance routine.

(5.2.7) *Screening Boxes and Ancillary Equipment.*

Adequate screening is essential in all photometric work. A series of screens built into a box, as illustrated in Fig. 7, is suitable for photoelectric and visual photometers.

It is convenient to provide a number of screening boxes of different types. If the dimensions of test plates and photocell holders are standardised, the apparatus

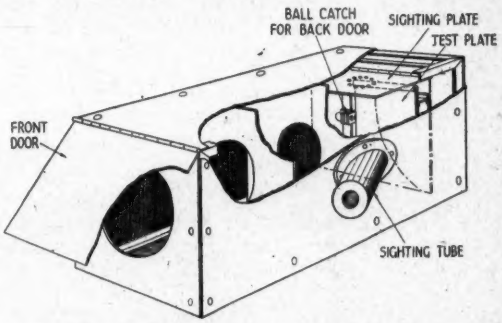


Fig. 7. Screening box for visual illuminometers and photocells.

is universal throughout the laboratory. Screens of this type are very effective and permit photometry in subdued general lighting in a laboratory with light walls.

Photometric screens usually have a matt black finish. It has recently become increasingly difficult to obtain suitable paints and black nylon flock spraying has proved to be very serviceable. Any matt finish has, however, a small but finite reflection factor and in many applications a polished black surface, suitably positioned to direct stray light out of the way, may be more satisfactory because its reflection factor, except at the angle of specular reflection, is lower than that of any matt surface.

(5.3) Colorimetry and Allied Problems

Colour measurements form an increasing proportion of the work of an illumination laboratory. Formal visual and photoelectric colorimetry is a specialised subject (33, 34, 7); the illumination laboratory is, however, better suited for commercial routine quality control using less elaborate instruments of the Comparator or Differential types, reference standards being obtained from a standardising laboratory. For example, coloured glasses for use in signalling systems are tested by comparing the colour and the transmittance of the sample with those of calibrated limit glasses. Details of this method of testing may be found in the Appendix to B.S. 1376.

(6) Mechanics of Fitting Photometry

In the pnotometry of fittings, measurements are required at any angle relative to the fitting and usually at such a distance that luminous intensity has a valid meaning. Measurements may have to be made at distances varying from a few feet to several hundred feet from the fitting depending on its size and optical system. The mechanical problems involved are often complex, typical difficulties being large size and weight, possible mechanical distortion of the fitting, the need for precise rotation over small angles with narrow beam projectors and instability of some lamps at some angles of tilt which makes it necessary to keep the lamp in a fixed orientation during the measurement.

Distribution photometers of many types have been described[35, 36] including, in recent years, elaborate designs for appraising fluorescent fittings[37]. The methods fall into three main groups and essential features of typical designs are summarised in the following sections.

(6.1) Short Range Distribution Photometers

In such apparatus, the measuring distance of the photometer may vary from a few feet to a maximum of about 30 feet when installed in normal sized rooms. The fitting is usually attached to a bearing plate so that it may be rotated in azimuth, and the photometer is effectively rotated in a vertical plane on the end of an arm centred on the fitting[38]. Arrangements of plane mirrors[35, 36] are normally used for the longer distances to avoid a long swinging arm.

Such distribution photometers are suitable for the majority of fittings utilising

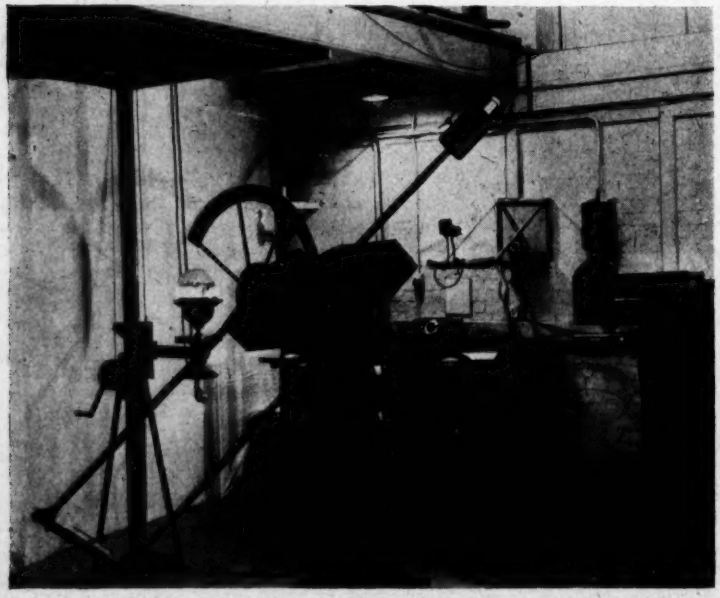


Fig. 8. Mirror distribution photometer with control table and screening box for photocell.

filament or mercury and sodium vapour discharge lamps and, provided the mirrors are large enough, for fittings equipped with the short fluorescent lamps.

One form of the apparatus is shown in Figure 8. This is of the two-mirror type in which the measuring distance may be varied from about 11 feet to about 24 feet by moving the photometer head across the room. The distance can be increased to about 38 feet by using a third mirror not visible in the photograph. A photovoltaic cell is housed in a screening box which, together with the black curtains surrounding the swinging arm and fitting, provides adequate screening. The photocell is connected to a galvanometer over the control desk and the galvanometer spot is arranged to fall on polar curve paper pinned to a turntable recessed into the top of the desk.

A handwheel is connected to this turntable and also to the swinging mirror arm by wire rope drives so that the operator sitting at the desk may move the mirror and paper together and plot the intensity distribution directly; a clutch enables the angular scale on the polar paper to be aligned with the angle of the mirror arm.

Two control panels are fitted. One contains the galvanometer sensitivity adjustment and switches giving remote control for the room lights and for local lighting. The second provides facilities for connecting electrical instruments into the test lamp circuit and includes control gear for the lamp.

Calibration is made by a substitution method. It is convenient to have a change-over device by which the test fitting is moved aside and the directional reference lamp brought into position. This gives a quick interchange between reference and test sources and avoids the difficulties of waiting for discharge lamps, particularly sodium lamps, to stabilise. Sodium lamps used for photometry must not be moved when hot, except very gently and smoothly, for the metallic sodium is liable to redeposit in different positions when the lamp is switched off and so alter the light distribution.

Visual calibration can also be made with a portable illuminometer and test plate. This requires that the measuring distance and the mirror losses are accurately known[36].

(6.2) Medium Range Distribution Photometers

Measurements of this type may best be described as turntable photometry; in general the fitting is mounted on a flat table capable of rotation in azimuth and of tilting in elevation. The light from the fitting is directed along the length of the laboratory to a stationary photometer, usually a photocell in a screening box. It is convenient if the galvanometer is placed near the turntable so that the effect of adjustments to the fitting can be seen directly by the operator.

The measuring distance is limited only by the dimensions of the laboratory and the sensitivity of the photocell/galvanometer combination. The apparatus is flexible and if sufficient distance for the purpose is not available in the laboratory measurements may be made in a long corridor, but measuring distances of more than 200 feet can introduce difficulties due to atmospheric absorption, particularly if the weather is misty.

Fittings measured on such apparatus include floodlights and small narrow beam projectors. The apparatus is also suitable for intensity distribution measurements of fittings incorporating fluorescent lamps, and Fig. 9 shows an example. The fitting is mounted in a framework on the turntable and the distance between the vertical posts may be altered to suit different lengths of fitting. Extra stiffening is sometimes necessary to prevent mechanical distortion when rotating the fitting about the horizontal axis. Care is needed when plotting the results obtained with this arrangement on an isocandle diagram, for the traces of the measuring directions in space differ from those obtained with the vertical distribution photometer[39]. Visual calibration or substitution methods are used for most types of fitting, but the calibration of fluorescent fittings presents particular measuring difficulties and allowance must be made for changes in lamp light output with orientation and ambient temperature[40].

In the appraisal of image projectors, spot lights and some fittings in which the

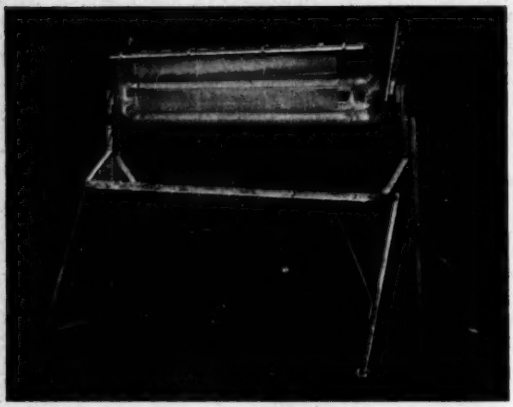


Fig. 9. Fitting mounted on turntable and goniometer for medium range distribution photometry.

lamp may not be tilted, the light is directed on to a white screen. An illumination survey is made on the screen from which the photometric performance of the fitting is calculated.

(6.3) Long Range Distribution Photometers

Intensity distribution measurements on searchlight projectors and the like need to be made over considerable distances. Ranges of the order of 200 to 500 yards are generally satisfactory; although distances up to 2,000 yards have been used, experience has shown that it is possible to photometer accurately at these shorter distances provided the projector is focused for the optimum flash[41]. With longer ranges measuring difficulties increase rapidly.

The photometric apparatus used differs from that employed in turntable photometry, chiefly in the sensitivity of the photometer and in the method of screening stray light. Additional apparatus such as a reference projector, flash camera, telephones and arrangements for measuring atmospheric transmission is also necessary[2, 41].

(6.4) The Measurement of Light Output Ratio

In the illumination laboratory the light output ratio is determined as part of the appraisal of a fitting, and can conveniently be calculated by integrating light distribution curves of the fitting. With the exception of large fittings used in interior lighting, where for the usual distance to the working plane intensity has no meaning, intensity distribution curves are always determined. They are used for many purposes, including calculation of the illumination reaching the working plane and derivation of utilisation co-efficients[42].

With large fittings, the measurement of sufficient distribution data to enable light output ratio to be calculated is lengthy, and if this quantity only is required the possibility of making a single measurement in a photometric integrator is attractive. This, however, requires careful consideration, for the fitting is bulky and usually has a light distribution very different from that of reference lamps used to calibrate the integrator.

Experience indicates that unless attention is paid to the size of integrator, to the quality and cleanliness of the paint, and correction is made for obstruction, errors are likely to occur. Many of these difficulties can be overcome if a calibrated fitting giving a similar light distribution is available, so that the two can be compared, but such " reference " fittings are usually available only if the work consists of routine checking on a restricted range of units.

An integrator capable of measuring present-day fittings accurately is very large

and expensive; it is by no means indispensible, and the considerable space it requires may often be more usefully employed.

(6.5) Fitting Rotators for Illumination Distribution

Restrictions on the use of intensity distribution data for calculating the illumination reaching the working plane from large light sources apply to many of the fittings designed for tubular fluorescent lamps, and for these illumination diagrams may be prepared, giving iso-phot (equilux) contours in convenient planes. A useful way of displaying the information is shown in Fig. 10, but the method is capable of many variations. Such diagrams cover a range of mounting heights and may portray the values of illumination falling on horizontal, vertical or inclined surfaces.

The preparation of these diagrams involves taking many readings at different mounting heights. The fitting is suspended at a particular mounting height, and the illumination falling at appropriate points on the floor is measured by portable visual or photoelectric photometers. It is usual to screen all stray light from the point of measurement, since the contributions from the walls and ceiling in an installation are not predictable. One exception is when measuring a fitting which emits a substantial proportion of its light upwards; the contribution from the ceiling is often appreciable and is taken into account by mounting the fitting on a white artificial ceiling.

Such measurements are possible with very simple apparatus, but this is satisfactory only if occasional measurements are needed and sufficient floor space is available. A better method is to rotate the fitting and take measurements along a fixed line below it. In this way a much smaller floor area is required and any corrections needed for cosine response of the photometer are simplified.

One example of such a fitting rotator is shown in Figs. 11a and 11b. A tube mounted in bearings in the roof structure may be raised or lowered by a winch; the fitting is mounted on a circular plate fastened to the lower end of the tube and is

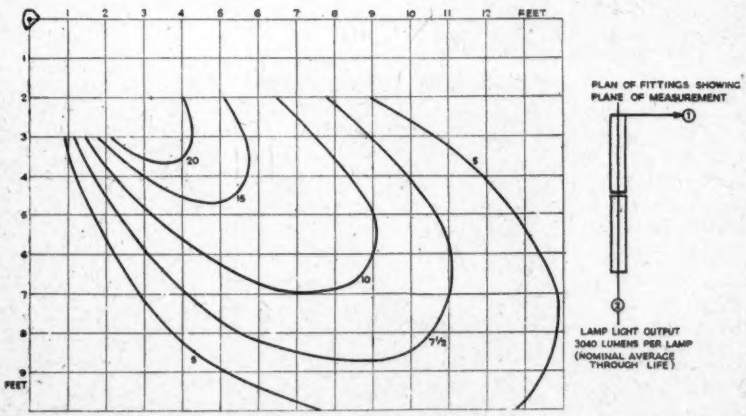


Fig. 10. Illumination diagram for two fluorescent fittings mounted end to end each equipped with one 80w. MCF/U lamp. Diagram shows illumination on vertical surfaces in lm/ft². Lines of equal illumination plotted in vertical plane(1) for surfaces parallel to plane(2).

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rotated in azimuth by a wire rope drive controlled from a hand wheel. Indicators on the wall show the height of the fitting above the floor and its orientation.

The photometer head consists of a photovoltaic cell on a carriage which runs along a track set into the floor; the photocell may be tilted and the angle is shown on a scale. The screening box used around the photocell has adjustable sides to allow for different sizes of fittings, mounting heights and angle of the photocell. Long leads connect the photocell to a galvanometer trolley placed near the controls which set the orientation and height of the fitting.

The apparatus described will carry a maximum load of 550 lb. and gives mounting heights up to 12 feet.

(7) Photographic Techniques

Photography is a particularly valuable tool in an illumination laboratory, for it is perhaps the only method of recording in any detail the visual impressions produced in completed installations. A well-equipped darkroom will be found useful both for experimental and record purposes.

More elaborate techniques may be used, of which the most valuable is Standard Representation Photography[43]. If the work demands it, photographic photometry[44] may be used, but the technique is difficult.

Typical photographic equipment might include a stand half-plate camera, a miniature camera and a darkroom with suitable enlargers for plates and 35 mm. film. Temperature control of developing equipment is needed for sensitometry and for photographic photometry[45], and for these purposes a densitometer or a contouring density comparator[46] will also be required.

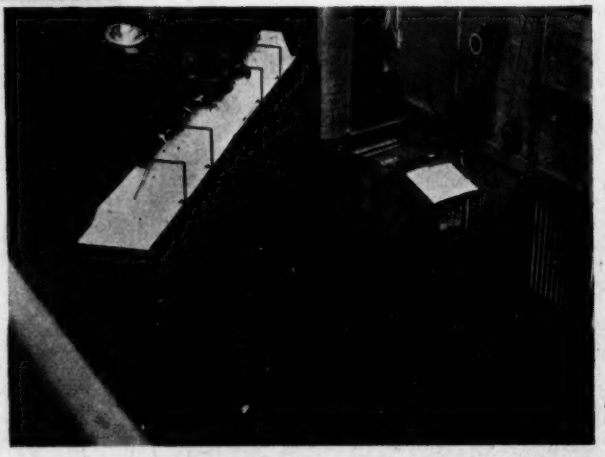

Fig. 11(a). *(Above)*. Overhead rotator for large fittings.

(b). *(Right)*. Rotator in use showing controls and scales on wall, galvanometer trolley and screened photocell.

Fig. 12. Enclosure for temperature measurements.

Such equipment may be used for the study of the photographic effect of light of various spectral distributions[47] and the luminance distribution in street lighting[44] or other installations.

(8) Thermal Testing

Nearly all lighting equipment involves problems of heat as well as of light and a laboratory concerned with development and testing requires facilities for temperature measurements[48]. Such investigations are required both to ensure satisfactory performance and to check compliance with specifications, e.g., B.S. 889. In practice, the time spent on thermal experiments may well exceed that spent on photometry.

(8.1) Temperature Measuring Equipment

The first requirement in thermal testing is to obtain steady and repeatable test conditions. An enclosure free from draughts can be achieved by the double-walled construction shown in Fig. 12, where the light metal framework is panelled in perforated metal. Natural convection around the fitting takes place, although due to the absence of draughts the test conditions are more severe than those obtaining in practice. From the experimental point of view, however, stable testing conditions are essential, and the more stringent nature of the test provides a factor of safety.

Measurements of temperature rise are made by thermocouples fastened to selected points on the fitting. These couples are connected to brass terminals kept at a uniform temperature by a cover, and copper extension leads run to a selector switch. The cold junction thermocouple, connected through the same terminal box, is immersed in liquid in a vacum flask, the temperature of which provides the reference temperature for the apparatus. A potentiometer circuit used to measure the potential difference between the test and cold junction thermocouples avoids the difficulties of change in resistance of the couple due to the temperature, and places no restriction on length of the couple. Iron-Eureka thermocouples are usually used, fine enough in gauge to avoid errors due to loss of heat along the wires.

Where lighting fittings cannot conveniently be tested in the enclosure a portable thermocouple equipment is used in which the thermal E.M.F. may be measured by

either a low-range millivoltmeter or a portable potentiometer. Useful information on these techniques is given in B.S. 1041.

Measurement of surface temperatures, especially of transparent materials of low thermal conductivity, is difficult. Fine wire couples may be cemented to the surface or strip couples retained in contact with it by suitable holders. Other valuable techniques are the use of temperature-indicating paints and resistance thermometers; the latter have been used, for example, for measuring wall temperatures of fluorescent lamps[49].

(8.2) Ventilation Problems in Lighting Fittings

A study of convection streams in lighting fittings is valuable when considering methods of reducing temperatures. One simple technique is to watch the path of smoke streams in the fitting; smoke may be generated by a small producer consisting of a heater coil wound round a narrow-bore glass tube filled with liquid paraffin. The tube can be placed at a suitable point in the fitting and the amount of smoke regulated by controlling the current. This device is illustrated in Fig. 13.

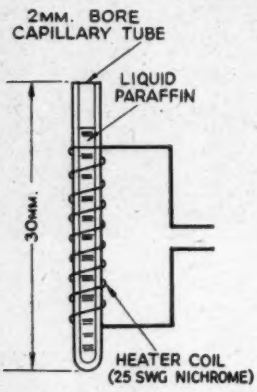

Fig. 13. Diagram of smoke producer for use inside fittings.

Hot air streams may also be studied by the Schlieren technique[50], which depends on the change in the refractive index of air with temperature, and enables photographic record to be made of the convection streams.

(9) Testing Component Parts of Fittings

Tests of materials and components of fittings are necessary to control quality, to check compliance with specifications or to investigate performance under service conditions. Reflecting and transmitting properties need some form of reflectometer[51], and perhaps a goniophotometer[52], or they may be tested by studying the effect on light distribution. Prism angles or reflector contours may need to be examined. Such tests may involve making plaster casts or sections and photographing them, or using specialised "raypath" apparatus[53]. The colour of colour filters for signalling purposes is conveniently checked on the bench against limit glasses (B.S. 1376), or for routine measurements in colour comparators built for the purpose. Enclosing diffusing ware requires testing to B.S. 324 for light output ratio, measured in the photometric integrator or calculated from light distributions; surface luminance is measured with portable visual photometers.

In addition to photometric tests, there are many mechanical and other tests, such as resistance to thermal shock and to rain, which may require a spray booth with calibrated spray[54, 55], an immersion tank with controlled temperatures (B.S. 324) or exterior life test stations. Watertight equipment and gaskets may need immersion or air pressure tests, and flameproof gear or glassware and some other equipment must be tested for shock in an impact test (B.S. 889) or for vibration on a shaking machine[55] or under a static load. It is also necessary to test materials and finishes, especially those for exterior use, for resistance to weather and corrosion[52, 55, 56]. The electrical equipment of fittings may have to be tested to specification for insulation resistance and in other ways, which may call for high-voltage test equipment and possibly a controlled humidity chamber. The point at which the responsibility of the illumination laboratory ends will depend upon the organisation concerned, but most laboratories must be fairly versatile, and will devise a good deal of specialised test gear for their own needs.

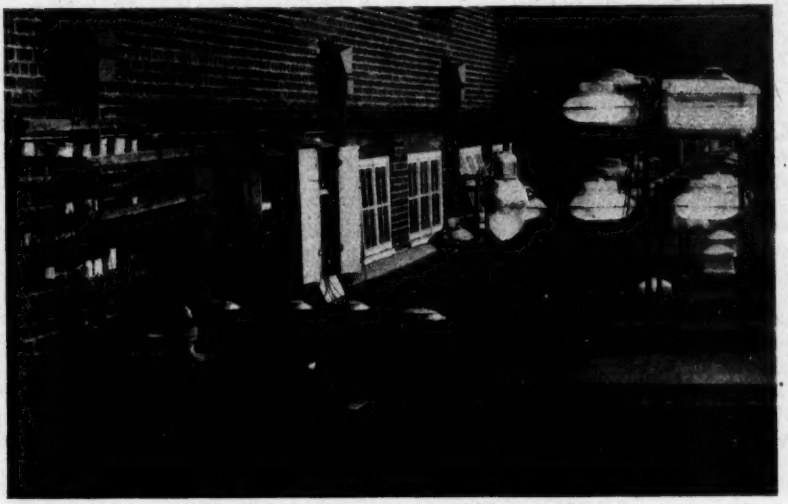

Fig. 14. Outdoor exposure and life test racks.

(10) Life Testing of Lighting Equipment

Life tests are lengthy and expensive to maintain, but may be necessary if service observations do not give the required information. Accelerated forms of test can sometimes be devised but unless care is taken to link them with service experience they may give misleading results. Life tests of complete fittings and component parts are therefore part of the routine work of an illumination laboratory and a typical outdoor test rack is shown in Fig. 14. This can accommodate a total load of about 20 kw. and is controlled by time switches and contactors which with the control gear for the fittings, is mounted in separate enclosures shielded from the weather. Weathering and corrosion tests made on a number of sites in different parts of the country are generally necessary(52).

(11) Field Tests

Evaluation of the performance of lighting equipment under practical conditions is frequently needed. Typical examples are measurements on completed interior and street lighting installations. One valuable function of such work is to check the accuracy of the final results with values calculated beforehand and in this way to acquire experience in predicting the performance to be expected under given conditions.

Field measurements are not easy since many of the factors cannot be controlled and high accuracy is not usually possible. Apparatus used in photometric tests, portable photometers, electrical instruments and the like should be robust and need checking before and after the test. Simple surveying equipment, telephones and other special apparatus may be needed including adequate transport facilities.

(12) Utilisation Problems

Studies of particular lighting problems may be simplified if the task can be removed from the field to the controlled conditions of the laboratory. This often requires apparatus built to simulate the practical conditions, which must be carefully

appraised to determine the fundamentals of the problem. Scale models are sometimes used in such investigations, and many other techniques have been described[57].

(13) Design of Building

An establishment covering the many branches of work reviewed needs careful planning if a large group is to utilise the facilities efficiently. In a small group, however, where relatively few problems are being investigated at any one time, interference between different experiments is not serious.

Essentially any illumination laboratory should include a room for photometry, with provision for a throw of at least 30-40 ft. if the work includes turntable distribution photometry of large lighting fittings. Arrangements to exclude daylight whilst retaining adequate ventilation are needed. The ceiling height should be sufficient to suspend fittings for test purposes and provision made to secure these easily. When the long throw is not required it is often convenient to divide the room so that the two parts can be used independently, for example, one part in daylight and the other darkened for photometry. The decorations should preferably be in light colours and matt black painting avoided.

Additional rooms are valuable for such specialised purposes as photographic work and thermal experiments.

Internal equipment of these laboratories should include adequate electrical and other services. Electrical supply panels for experimental work are, for example, best wired to a central distribution board so that any of the available supplies may be connected. In addition ring mains providing a low voltage supply for galvanometer lamps and mains voltage for general purposes are useful.

Many additional features can be incorporated and these are best illustrated by considering a building specifically designed to cover the problems described in this paper. It is of single-storey construction[58] with motor-driven blinds on north lights

Fig. 15. Illumination laboratory in a large establishment.

and covers a floor area of about 5,000 sq. ft. The internal layout, due principally to the late G. H. Wilson, consists of the main laboratory, 90 ft. long by 30 ft. wide (Fig. 15), together with five subsidiary laboratories and office accommodation. A projection room at one end of the main laboratory is equipped with film and lantern projectors, and a further projection room is provided for the outdoor photometric range.

In the main laboratory, which can be divided by sliding doors, the end wall is painted white to form a projection screen. An overhead track carries a further projection screen which can be lowered at any point along the laboratory. The track also carries a gantry with lifting tackle and a traveller for handling heavy fittings and apparatus. Cable troughs run both along and across the floor to avoid trailing lengths of cable joined to apparatus and a centre guide rail in the floor is used for moving or setting up apparatus in a straight path along the full length of the laboratory. The platform, which extends along one side of the main laboratory, forms a convenient mounting for some fittings and is also used for model experiments. Master control buttons fitted at many points throughout the main laboratory operate contactors for the room lights.

Three of the subsidiary rooms are equipped for bench photometry and small optical tests, thermal experiments, and spray testing. The department also has a photographic dark room and a local workshop.

In addition to the necessary electrical supply points, gas, water and compressed air services are available. Drain holes are provided in the floor at several places. A telephone line links the projection room to points along the main laboratory.

(14) Conclusions

This paper has reviewed the more usual types of problem which occur in the illumination laboratory; the wide scope of these problems, and the extent to which technologies other than photometry are utilised in their solution, has been noted.

Whilst in the small laboratory only simple basic equipment may be available, the skill and the resourcefulness of the experimenter, backed by suitable reference standards provided from the standardising laboratory, enable much useful work to be done. The demand for elaborate equipment occurs when the volume and urgency of the work is great and speed of measurement is important. Whilst in this review it has only been possible to outline the principles of the apparatus, more elaborate designs have been devised for many applications giving increased speed, convenience or precision of measurement.

Usually, however, ability to improvise from simple apparatus is needed to meet the varied nature of the problems, and flexibility in the equipment is often more valuable than the limited scope of complex and elaborate gear. In general it is better, in setting up a new laboratory, to devise and construct new apparatus as the need arises, than to attempt to anticipate all possible demands by installing equipment which may stand idle for most of its life.

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Discussion

DR. J. W. T. WALSH: I think we must all be lost in admiration of the paper to which we have just listened: the thing which astonished me particularly was the tremendous amount of ground which Mr. Stephenson managed to cover in the course of one paper—I think if he had done himself justice we should have had a series of three or four papers all as interesting as this one.

I was very glad that at the beginning he drew such a marked distinction between the photometric laboratory proper and the applied photometric laboratory or illumination laboratory, because the two are very different.

I would like, first of all, to refer to the measurement of luminous flux from lamps and fittings, particularly the important measurement which he mentions in the paper of the light output ratio. The author gave me the impression that he felt the measurement of the luminous flux from a large fitting, such as a fluorescent lamp fitting, was a very laborious and difficult process. I am sure that many people are scared at that particular measurement for large fittings. They argue, that, not having a sphere or integrator large enough to take the fitting, the only thing to do is to measure the light distribution curve and integrate that. They then assume that if the fitting is about 6 ft. long it is necessary to take measurements at a distance of about 60 ft. to get the true distribution curve. They do not always realise that you can calculate flux from an erroneous distribution curve obtained by making measurements at a constant distance of, say, 5 or 6 ft. around the fitting. The curves you get will be quite wrong as distribution curves but they can be integrated to give total flux. I would like to ask Mr. Stephenson whether he has had any experience with that method of measuring total flux.

He mentioned the different forms of apparatus used for measuring light distribution curves from projection apparatus, which may include anything from miners' cap-lamps to searchlights. In the case of long-range distribution measurements, he did mention atmospheric transmission, but I have known atmospheric transmission give trouble even with a fairly short range in a laboratory—unless you insist on a no-smoking rule.

Personally, I am a very keen advocate of black walls for photometer rooms. I know that there are many who think otherwise, but I still feel that it is a good thing to have this extra precaution against stray light.

I do not think there is any mention in the paper of a very valuable piece of equipment, but one very difficult to obtain: I refer to a standard of reflection factor. This

looks a very innocent piece of glass, but the trouble involved in standardising it is almost unbelievable.

MR. F. JACKSON: As the lives and often the efficiencies of lamps are adversely affected when they become overheated in fittings, the illumination laboratory must make strong recommendations on behalf of the lamp manufacturers when they find instances of inadequately ventilated lanterns. From time to time, reports of short lamp lives or other lamp defects are traced back to badly ventilated fittings.

In our experience on weathering tests on fittings, the illumination laboratory is ideally placed for selecting and analysing data from actual installations. Where possible this data should be obtained by members of the laboratory visiting the installation and inspecting lanterns, but where lighting engineers in the field report the same defect on the same lantern from different installations, regard can be taken of this. This information when married to the laboratory weathering tests, presents a truer picture than does the laboratory testing data alone.

The medium-range turn-table photometer described by the author is not connected to a continuous plotting table as is the short-range instrument. In our laboratories when fittings of comparatively narrow beam are measured, we feel that a continuous plotting table is essential if the candlepower variations within the beam are to be measured accurately. Where readings are taken at 1 deg. intervals, the resulting polar graph is often untrue due to large changes in candlepower between each reading.

Visual photometers are defective in two ways. Firstly, for reasons of convenience, the standard lamp in the instrument is a tungsten filament lamp and, in consequence, the standard reference surface is illuminated by light of a particular colour. When measuring a surface illuminated with high-power mercury vapour lamps, it is difficult to reconcile the colour difference and even when correcting filters are used the point of equal brightness cannot be found with high accuracy. It appears, therefore, that for reasonably high intensities a flicker head has advantages over the Lummer-Brodhun contrast prism.

Secondly, the accuracy of the visual instrument decreases with the intensity of illumination when this is below about 5 lumens per sq. ft. Can the author indicate what he considers is the lower limit of the instrument when an accuracy of $\pm$ 5 per cent. is required?

MR. G. FAHEY: The author mentions typical problems arising in an illumination laboratory, but most of the information concerns small sources, and there is very little concerning larger sources where the problems are more varied and less easy of solution. Dr. Walsh has mentioned the minimum distance for measuring large sources —has the author any information as to the relation between the minimum distance and the size of the source? Also he mentions that the accuracy of the measurement depends on the ratio used. Has the author any information from his own experience regarding the accuracy to be expected between a 5:1 ratio and a 8:1 ratio?

Regarding Section 6.2, I feel it would be misleading to say that the change in light output with orientation, and ambient temperature are the only two difficulties in the light measurement of fluorescent sources, others being the colour of the lamp, run-up period, type of control gear and the age and the efficiency of the test lamps. Could the author say from his own tests if he has any recommendations in this direction?

Section 6.4, on light output ratio, seemed very non-commital to me. In the first paragraph the author states that light distribution curves of large sources are not generally made. In the second paragraph he mentions that a method which he has already used is very lengthy and refers to the quicker method of using an integrator, and further says that the integrator is not indispensable. Could the author state which

he would recommend and if there is any comparison that can be made between figures obtained by the lengthy method and the photometric integrator ?

I searched the paper closely to find a method of arriving at co-efficients of utilisation of large sources. Could the author say if he has had any success in such determinations ?

In determining equilux diagrams (6.5) for substantially upward illumination fittings, the author recommends a false white ceiling. Does the size of the ceiling bear any relation to the size of the source ? It is held that the size of the ceiling should take in all angles at which the upward illumination occurs; if so, the false ceiling should be used with any fitting which has upward illumination.

MR. H. E. BELLCHAMBERS: The author has undertaken an onerous task in attempting to describe in detail all the functions and equipment of an illumination laboratory. A glance at Table I gives some idea of the scope of the task. Evidently it is difficult to cover all the points sufficiently and some parts have to be just touched upon. I feel, however, that the stress has been placed on the wrong items.

I wonder whether the author really intended Table I to be a list of problems; surely this is a list of functions of a laboratory. For instance, item 9, " Photography," is not a problem of illuminating engineering but is (as the author says at the beginning of the paper) " a means to an end."

I think one should be very careful to use intensity measurements correctly. The author has mentioned that the distance at which you can use these measurements does depend on the accuracy to which you wish to work and he states that an absolute accuracy of 5 per cent. is usually sufficient. I agree that this is a desirable aim, but I would add that often it is difficult to maintain.

Regarding the value of intensity measurements from large sources, and in particular fluorescent fittings, after checking, by referring to Dr. Walsh's " Photometry," I concluded that you could maintain the accuracy which the author suggests if you use intensity measurements at distances greater than 6 ft. 6 in. from 5 ft. sources.

Section 4 is headed " Fundamental Equipment Common to Photometric and Illumination Laboratories." My understanding of fundamental equipment is equipment used for fundamental measurements, and this work is generally done at the N.P.L.

In the written paper the author describes at length luminance meters and illumination photometers and makes reference to very low levels of luminance; I think perhaps the author could well add to his references that of P. H. Keck in Optik volumes 4 and 5, 1949, where such measurements are discussed and an instrument is described capable of an accuracy of 50 per cent. at levels of 10-5 foot lamberts.

In describing the mechanics of fittings photometry the author rightly stresses the difficulties involved in the photometry of fluorescent fittings; you have to wait some time for the fitting to stabilise before making measurements, and the process is tedious. In this section of the paper the problem of obtaining data for fluorescent fittings for illumination calculations and co-efficients of utilisation has been mentioned. In the laboratory with which I am associated we can obtain co-efficients of utilisation by taking measurements at distances up to 50 ft. and then applying the method of Harrison and Anderson, taking mean values in a number of planes.

Incidentally, I have measured total flux output by taking measurements at short distances and have found that generally this is within the accuracy at which we expect to work.

It seems to me that there is danger of errors creeping in when using a spot galvanometer in distribution photometers to give direct readings in candlepower, and we prefer to plot each point separately, reading off from the galvanometer and noting

the value. It does give an opportunity of frequent zero checks which I feel is very important.

When making illumination measurements from fluorescent fittings with large quantities of upward light, I feel there is extreme danger in taking readings of fittings suspended from white ceilings unless you issue data for a variety of distances from the ceiling, and specify the reflectance of the ceiling; innumerable inaccuracies are likely to come in.

Utilisation problems have been dismissed in the paper in one paragraph, but I feel that the author has put that right to some extent by the slides which he has shown. Further descriptions of the method and the equipment used in this kind of work would have been of value and interest.

DR. F. W. SHARPLEY: Reference is made to the use of an emission-type photometer fitted with a Preston liquid filter. I feel that the necessarily brief comments in the paper barely do justice to the usefulness of either the photometer or the filter. A great advantage of the photometer is that, as the author states, it provides a photometric scale in itself. The necessity of providing adjustment in distance between the light source under measurement and the photometer is therefore avoided and dependence on the inverse square law is eliminated. This must be classed as a major development in photometry. The use of a Preston liquid filter specially prepared to suit the particular photoelectric emission tube adds to the above advantage that of very nearly perfect colour correction, and thus eliminates the tedius and time-consuming visual photometry requiring a number of trained observers having normal or nearly normal colour vision.

It would be of interest if Mr. Stephenson could say from his experience whether the colour correction provided with a Preston liquid filter alters appreciably during the life of the photocell with which it is used.

MR. F. C. SMITH: I was extremely interested in the accelerated life tests shown, but I think one ought to sound a note of warning in all these tests that they are of little value unless co-related with outside experience. I was, however, worried when I heard Mr. Jackson say that his best source of information was from one or two people who might come in and say that a certain lamp had failed. In my industry we make tests on a variety of things, and we find that people who make one or two observations in the field and then bring back their results to the laboratory without full details of what they have done may cause you to go after something which is not really of interest because the things are not adequately reported. We attempt to get over that by instituting field tests, where we put these things into predetermined places, issue questionnaires and follow most carefully the results of the questionnaires; by analysing these tests one finds where there is a real weakness which the accelerated life tests have not exposed in the laboratory.

I was interested in Dr. Walsh's remarks on total flux. We have to measure total flux of infra-red. It is quite true that with large sources you can get the total flux quite accurately with small distances.

I was very interested in the methods for temperature measurement. Temperature measurements are not easy, and I wondered if the screens used to avoid unwanted draughts did not introduce too artificial a condition.

DR. W. E. HARPER: One of the most valuable features of a review paper can be the list of references, and our thanks are due to Mr. Stephenson for the considerable list which he has compiled.

If we are to obtain satisfactory results from our experimental work we need more than the skilful use of apparatus; we need to lay out our experiments with care. Most

of us to-day are faced with limitations of cost, materials and labour, and our work must be planned to obtain precision with economy. For evaluating materials we have found multiple factor experiments to have great value, and I should be interested to know whether Mr. Stephenson uses similar techniques in photometric work. The factorial experiment might be a powerful tool for determining economically the significance of the errors and variables involved in the photometry of fittings.

Regarding weathering, I agree with Mr. Stephenson that accelerated tests can give misleading results. Field and service trials are always preferable, but their usefulness is frequently limited by failure to record the relevant meteorological data. We collect masses of performance data, which it is difficult, if not impossible, to interpret with confidence through our neglect of the variables controlling the performance. In our own work on the weathering of plastics we found it necessary to set up a recording station adjacent to our test ground before we could analyse and rationally apply the results of exposure trials. Weathering tests on lighting fittings are presumably more complex than tests on materials, and I should be interested to hear from Mr. Stephenson to what extent he is able to correlate the performance data from the various weathering stations mentioned in his paper with the relevant meteorological data.

MR. J. M. WALDRAM: I wonder whether members have read the Presidential Address of Sir Harry Ricardo, when he was President of the Institution of Mechanical Engineers. Mr. Stephenson's paper recalled it to me. Sir Harry was talking about laboratory work in another field, that of the study of internal combustion engines, but his remarks apply generally. He said, to those about to equip a laboratory, that it is far more important to spend money on the men than on the equipment. He recalled having seen in other countries luxuriously equipped laboratories in which, in his estimation, it was impossible for anybody to find out the idiosyncrasies of all the equipment in a lifetime. He had seen solemn papers discussing phenomena which he was convinced were errors of the measuring equipment rather than characteristics of the apparatus under test, and he described this over-elaborate instrumentation as "pure eyewash." Those who have the problem of equipping a laboratory may wish to bear these words in mind.

Another writer, in another field of experimentation, said, "Happy is the man who hath only one method of measurement, for he that hath more shall be discomfited"—an aphorism which may have a bearing on the discussion of photometric integrators.

I support Mr. Stephenson's plea for light decorations. The screening box which he has demonstrated is thoroughly effective; even a 2-kw. spotlight directed on it at about 45 deg. from the axis caused no perceptible shift of the spot. A black room is a temptation to omit proper screening, and may well lead indirectly to more errors than it will avoid; and for an illumination laboratory, concerned with other matters than pure photometry, normal decorations are valuable.

I would like Mr. Stephenson to give us an idea of where one should begin to start a small laboratory with small funds: what is the fundamental equipment? I take it you must have a photometric standard, and a photometric scale, and some practical photometers. What are the simplest things one can begin with?

MR. H. F. STEPHENSON (replying to the discussion): Attention has rightly been drawn by Mr. Bellchambers to the difficulties involved in describing adequately the wide field of activities reviewed in the paper, and he and Mr. Fahey have criticised the brief treatment of some sections of the work. In view of the need to compress a large amount of information into the available space I was content to refer to existing literature wherever possible and to describe in detail matters not elsewhere discussed. It was also necessary to confine the paper, as the title states, to "the equipment and

functions of an illumination laboratory." Much of the discussion has dealt with questions of experimental procedure and techniques in one limited field of measurement and most of the points to which Mr. Fahey and Mr. Bellchambers refer will be found to be adequately covered by the references. In this connection the bibliography contains in most cases only the more recent papers, but these give many useful references to earlier work.

I am indebted to Dr. Walsh for reminding us that photometric measurements may be taken at a relatively short distance from a fitting and used to integrate the light flux from it. This is a useful technique and gives the correct result provided the photometer obeys the cosine law over the angle subtended by the fitting.

It should be remembered, however, that in the calculation of coefficients of utilisation using Harrison and Anderson's data, a mean light distribution curve is needed, measured far enough from the fitting for the conception of luminous intensity to apply with sufficient accuracy. Measuring distances of the order of 25 ft. from a 5 ft. source will give a sufficiently close approximation and I feel Mr. Bellchambers could, with advantage, reduce the measuring distance he uses from 50 ft. and have much more light available to measure. With regard to the measuring distance of 6 ft. 6 in. from a 5 ft. source which he quotes, this will introduce a systematic error of minus 5 per cent., whereas the paper refers to an overall accuracy of $\pm$ 5 per cent.

I support Dr. Walsh's remarks on a standard of reflection factor and would put forward a plea that the characteristics of suitable reference surfaces should be studied by a standardising laboratory, preferably at the N.P.L. Another paper on this important subject is long overdue and would be of great assistance to many photometric and illumination laboratories.

The fundamental apparatus needed when equipping a small laboratory depends so much on the class and scope of work to be undertaken, space limitations and the funds available, that it is not easy to reply satisfactorily to the important practical question raised by Mr. Waldram. Probably the simplest set of equipment might comprise a wide range photoelectric illumination meter of good quality, with a simple photometer bench and directional reference lamp with which it may be calibrated. Suitable electrical measuring instruments and supplies both for the reference lamp and for light sources under test will be needed. A simple distribution photometer or a turntable is desirable and the illumination meter could be used as the photometer. If sufficient funds are available a galvanometer trolley and photovoltaic call (see Section 5.2.5) will provide greater sensitivity and versatility. Finally a simple visual photometer of the S.E.I. type (see Ref.: 16) should be available.

In a somewhat larger laboratory extra apparatus might be added such as a "Universal" photoemissive photometer with "average eye" correction, a precision visual illuminometer and a more elaborate distribution photometer. It should be remembered that more precise photometric equipment may demand the provision of better quality electrical measuring instruments and more stable power supplies if full advantage is to be obtained from the apparatus. In addition, as the scope of the work increases it may be necessary to add to the dark room space available for experimental work. Non-photometric test gear will also be needed, starting perhaps with a set of temperature measuring equipment.

Dr. Forbes-Sharpley's comments on the advantages of the "Universal" emission-type photoelectric photometer amplify the necessarily brief description in the paper. We have experienced no appreciable change in the characteristics of the Preston-type liquid filter during life unless accidental damage to the glass cell, resulting in failure of the air-tight sealing, has occurred. In general, the spectral response of the photocell itself does not alter appreciably when kept at a constant temperature. Occasionally small changes have been detected, but the magnitude of these changes has been

comparable with the residual small departures from "average-eye" data which remain when liquid filters are used for correcting the spectral response of the photocell. The changes, however, may be significant with the more precise correction obtained in photometers of the dispersion system and mask type.

With reference to the difficulties of visual heterochromatic photometry mentioned by Mr. Jackson, the accepted technique is to use a 2-deg. photometer field with colour-matching filters* to minimise the colour and spectral energy differences. Flicker photometers enable a photometric match to be made without colour difference so that an individual observer obtains consistent results. Observer differences, however, still remain, due to lack of an energy match and the Lummer-Brodhun contrast-type of prism with a 2-deg. field and colour-matching filters is to be preferred.

The C.I.E. "average-eye" data apply to field luminances of the order of 25-equivalent-metre candles (about 2.5 foot-lamberts) or higher. At lower values of the order of 0.5 foot-lamberts the Purkinje effect begins to operate, and the accuracy depends on the energy differences involved so that no precise data can be given. In addition, the contrast sensitivity of the eye decreases at lower brightness levels and this limits the precision of measurement.

I am indebted to Mr. Bellchambers for the reference to Keck's papers on a low-brightness photometer.

I would endorse Mr. Smith's remarks on the difficulties of temperature measurement. Extreme care is necessary in this work to obtain reliable and consistent results. The double-walled enclosure, described in Section 8.1, effectively reduces unwanted draughts and, provided the enclosure is large enough, no significant changes occur in the temperature of objects under test due to heating of the walls by radiation. The temperature thus recorded may, however, be higher than that obtained in practice if the fitting is normally used in a draughty situation.

Dr. Harper's remarks on the importance of designing experiments with care are a timely reminder that, even with the most precise and elaborate apparatus, an experiment will only answer the question asked of it if very carefully planned. Statistical methods are of great value in some of the experimental work of an illumination laboratory and the multiple-factor technique provides a powerful and economic tool, particularly where there are a number of inter-related variables.†

I agree that the collection of meteorological data at weathering stations can assist greatly in the interpretation of the results of such tests. The practical difficulties of collecting such data, however, are often considerable, particularly when the test station is many miles from the laboratory and frequent supervision of the apparatus is not possible.

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* Report on Visual Photometry, C.I.E. Compte Rendu des Séance, 1948, p. 178.
† Industrial Experimentation, by K. A. Brownlee (H.M.S.O., 1948).

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